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8 **Eruptive history of the Ubehebe Crater Cluster, Death Valley, California**
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Abstract

A sequence of late Holocene eruptions from the Ubehebe Crater cluster in Death Valley was short-lived, emplacing several phreatomagmatic and magmatic deposits. Seven craters form the main group, which erupted along a north-south alignment 1.5 km long. At least five more make a 500-m east-west alignment west of the main crater group. One more is an isolated shallow crater ~400 meters south of that alignment. All erupted through Miocene fanglomerate and sandstone, which are now distributed as comminuted matrix and lithic clasts in all Ubehebe deposits. Stratigraphic evidence showing that all Ubehebe strata were emplaced within a short time interval includes: (1) Deposits from the many Ubehebe vents make a multi-package sequence that conformably drapes paleo-basement topography with no erosive gullying between emplacement units; (2) Several crater rims that formed early in the eruptive sequence are draped smoothly by subsequent deposits; and (3) Tack-welded to agglutinated spatter and bombs that erupted at various times through the sequence remained hot enough to oxidize the overlying youngest emplacement package. In addition, all deposits sufficiently consolidated to be drilled yield reliable paleomagnetic directions, with site mean directions showing no evidence of geomagnetic secular variation. Chemical analyses of juvenile components representing every eruptive package yield a narrow range in major elements [SiO_2 (48.65-50.11); MgO (4.98-6.23); K_2O (2.24-2.39)] and trace elements [Rb (28-33); Sr (1513-1588); Zr (373-404)]. Despite lithologic similarities, individual fall units can be traced outward from vent by recording layer thicknesses, maximum scoria and lithic sizes, and juvenile clast textural variations. This permits reconstruction of the eruptive sequence, which produced a variety of eruptive styles. The largest and northernmost of the craters, Ubehebe Crater, is the youngest of the group. Its largely phreatomagmatic deposits drape all of the others, thicken in paleogullies and thin over several newly created crater rims. Evidence in-hand virtually requires that the Ubehebe cluster of craters erupted over a brief time interval, not protracted over centuries.

Keywords: Ubehebe Crater cluster; Death Valley; maar volcanoes; phreatomagmatic; tephra stratigraphy

1. Introduction

Ubehebe Crater is one of a cluster of closely spaced young mafic craters in northern Death Valley, California (Fig. 1). Situated at the north end of the Cottonwood Mountains and resting on thick, indurated Miocene fanglomerate and sandstone, the crater cluster is a picturesque desert scene that has long been a tourist destination. Ubehebe Crater (Fig. 2) became a focus for the California Volcano Observatory (CalVO) of the USGS a few years ago when ^{10}Be surface exposure dating by Sasnett et al. (2012) suggested that a series of eruptions from the cluster spanned as much as 4300 years in the late Holocene. Their conclusion that the ^{10}Be data indicate protracted activity at the crater cluster contradicts the common volcanological wisdom that such clusters are monogenetic and short-lived. The study, therefore, elicited widespread skepticism, but it raised concern about the potential eruption hazard and prompted the current investigation of the craters and their eruptive products. Ours is largely a stratigraphic study of the deposits, resulting in inferences from the layering about the timing and sequence of multi-crater activity and about the hazards implications.

2. Previous work

Reconnaissance by von Engel (1932) recognized two craters, and Clements (1954) later recognized seven, but no detailed studies were attempted until Crowe and Fisher (1973) outlined 13 craters, and focused on the largest of them, Ubehebe Crater, which they recognized as the youngest. Most of their work detailed the sedimentological character and emplacement mechanisms of base surge deposits from Ubehebe Crater. The most recent work was by Sasnett et al. (2012), who used ^{10}Be surface exposure dating to estimate emplacement ages of quartz-bearing lithics in the phreatomagmatic ejecta around Ubehebe Crater. Interpreting the resulting ages without a stratigraphic context for the clasts analyzed, however, led to conclusions that are at odds with volcanological observations. For the first time, our paper describes deposits from all of the craters, identifies eruptive units and source vents for each, and presents whole-rock chemistry that is tied to stratigraphic relationships. Paleomagnetic determinations by D. Champion (Fierstein et al., 2016; Calzia et al., 2016) are also put in the context of our established eruptive units. Our stratigraphic study shows that all of the clasts dated in the ^{10}Be study were

part of the Ubehebe Crater deposits and were ejected only from Ubehebe Crater, so that the range of ^{10}Be ages (between 0.8 and 5.1 ka) cannot be attributed to clasts derived from older adjacent craters. A more in-depth discussion of how the paleomagnetic data inform interpretation of the Sasnett et al. (2012) ^{10}Be ages is the topic of another paper (Champion et al., in prep).

3. Methods and Terminology

A total of 27 field days in Spring and Fall months between 2013 and 2016 were spent establishing traceable units, measuring their thicknesses and distributions, and considering the characteristics of each with distance from vent, permitting reconstruction of the sequence of eruptive events that produced the cluster. Overall, 46 sections were measured and logged, 30 clasts were analyzed for whole-rock composition, and 5 sites that span the sequence of eruptive events were cored for paleomagnetic directions (Fig. 3).

Ubehebe Crater has been cited as a classic example of a maar volcano (e.g., Fig. 4 of White and Ross, 2011), with the general understanding that maar eruptions are the result of magma interacting with water (e.g., Lorenz, 1973, 1986, 2007; White and Ross, 2011; Valentine and White, 2012). These studies have addressed eruptive mechanisms at maars, while others focus on emplacement processes of the deposits, as did Crowe and Fisher (1973) at Ubehebe Crater. Our study does not delve into either, however, but rather focuses on establishing the sequence and timing of eruptive events at the Ubehebe crater cluster, which provide the framework necessary for any such future work. To clarify our use of terminology for descriptive purposes, we herein use the term “phreatomagmatic” for deposits that include a range of proportions of dense juvenile basaltic clasts, milled (recycled) basaltic clasts, accidental lithic fragments, and bread-crust bombs with included lithic fragments; and “magmatic” for deposits with a predominance of highly vesicular (well-inflated) juvenile basaltic clasts with only small lithic contributions.

4. Overview of the crater cluster

As many as 14 arcuate to circular depressions make up the Ubehebe crater cluster (Figs. 1, 3). The largest and northernmost, Ubehebe Crater proper, is ~800 meters north-to-south, rim-to-rim. The view (Fig. 2) from the parking lot on its west side is impressive—toward a steep east wall that drops as much as 165 meters to the crater floor. Just south of the big crater is a shallow 600-meter-long depression here called the Amphitheater, which has southern, middle, and northern segments, each with low arcuate walls (Fig. 3). Little Hebe Crater is wholly nested within the northern segment.

Adjacent to and west of the Amphitheatre is a discrete 170-meter-wide crater designated “P” (Fig. 3). An adjoining alcove of similar size is of uncertain origin. Although its circular shape suggests a crater and not an avalanche scar, no ejecta are known to have been derived from it. A small amount of predominantly recycled ejecta exposed nearby could have been derived from the alcove, but the deposits are not voluminous enough to explain its size. Instead, the smooth horseshoe shape may reflect its enclosure by adjoining craters, augmented by a small amount of explosive activity.

Deposit “S” on Figures 1 and 3 marks a broad scoria slope, the remnant of an early scoria cone that was later explosively truncated both north and south by the Ubehebe and Amphitheater eruptions. The 7-8 vents that form the main group thus define a 1.5-km-long, north-south alignment. Six more craters form the 500-meter-long Western Crater group, for only two of which have ejecta been identified—one with a significant magmatic component, the other with a large fraction of lithic and recycled basaltic clasts. The other four depressions—all fairly shallow—are probably vents, but any deposits are now mantled by the youngest deposits from Ubehebe Crater. One more, Crater T, is an isolated shallow crater to the southwest. All together, 10 vents have been identified that produced ejecta: “S” scoria; southern, middle, and northern Amphitheater sources; Little Hebe; Crater P; Western Craters W and Z, Crater T; and Ubehebe Crater. The total would be 11 if the alcove were also explosively formed. Only Ubehebe is a deeply excavated crater. Although called craters here, most of the others are shallow and have walls largely of constructional origin that might better be called ejecta rings.

The deposits collectively drape a well-developed pre-existing network of gulches, which have now been reincised through the ejecta, largely along the same pre-eruptive drainage axes (Fig. 4). The contact between basement rock and volcanic ejecta is seen along most of the gulches. The basement here is thick Miocene fanglomerate —made up of consolidated layers of fan deposits with a variety of well-rounded cobbles, intercalated with orange, yellow, and white sandstone lenses (Fig. 4). Fanglomerate cobbles and angular chunks of sandstone were ripped up during eruptions and incorporated into all of the ejecta layers. The reincised drainages provide good exposures of the ejecta, permitting correlation of layers from one gulch to the next. The main gulches along the east side of the Amphitheater are designated Gulches 1—4, north to south (Fig. 3). Large gulches east and south of the Amphitheater are also labeled in Figure 3.

The youngest of the vents here is Ubehebe Crater; its strongly stratified deposits drape the landscape and are the topmost package of ejecta. Dozens of layers from Ubehebe Crater are all conformable, with no alluvial channeling or rilling between any of them. Nor is there any channeling or rilling between deposits from any of the other craters (Fig. 5). From oldest to youngest, we detail below the sequence, characteristics, distribution, and between-unit relations that lead us to conclude that there was little time between explosive events, and that the sequence of eruptions from the crater cluster was of short duration.

4.1 Initial Scoria “S”

The first eruption in the sequence was dominantly magmatic and produced a relatively widespread scoria fall that, wherever exposed, lies directly on basement. It includes a thick scoria fall that makes a striking black wedge on the SW wall of Ubehebe Crater, a patchily exposed pile of locally agglutinated scoria on the SSW-wall, a thoroughly oxidized, agglutinated pile of large scoria bombs on the S wall, (Fig. 6; “S” on Fig. 3), and a block-rich black fall on the SSE wall. It was the largest of the magmatic eruptions, with >15 meters of fall deposits exposed proximally, >4 m exposed in the walls of Crater W, with a few bombs as big as 12 cm ~750 meters NW, and a 40-cm-thick black scoria fall with scattered large, flattened bombs up to 2 meters across 750 meters SE in Big East Gulch (Fig. 7a). Distal primary fall is sparsely preserved but has been found up to 5 cm thick at one location 4 km to the east and up to 1.5 cm thick 5.5 km to the NE (Fig. 8). Most of the scoria clasts are moderately to highly vesicular,

well-inflated pyroclasts, and—in contrast to almost all later units—the deposit is extremely lithic-poor.

The “S” scoria fall is exposed as a northward-thinning wedge on the SW wall of Ubehebe Crater where it rests sharply on pale orange sandstone at 770 m elevation and contrasts sharply with the 20 meters of strongly stratified tan and grey phreatomagmatic Ubehebe Crater layers above. Gullies that cut to the base of the scoria-fall wedge show it to be as thick as 15 m. The moderately to highly vesicular scoria are typically 1-4 cm across and a few are as big as 7 cm, but denser, cauliflower and breadcrusted ballistic bombs up to 75 cm are scattered throughout the deposit. The denser bombs commonly have a few angular white lithic inclusions, but the more inflated scoria have none. Fanglomerate cobble lithics in the fall matrix are scarce, though present, especially in the lower part of the fall that is (poorly) exposed in the southwest corner of the Ubehebe Crater wall. Most are small (0.5—3 cm), but some pods and discontinuous stringers of larger lithics (5—10 cm) are exposed there. The proportion of highly vesicular scoria increases upward, with the top meter of the deposit made up entirely of delicate, vesicular scoria that stand out as a coherent ledge, not because they are agglutinated, but rather because their rough surfaces hold the deposit together. Scattered meter-size spindle and breadcrust bombs, also inflated, are scattered along the top of the black ledge.

Scoria-fall deposits exposed along a 350-meter stretch of the south wall of Ubehebe Crater are typically coarser than those in the SW wall, but are similarly lithic-poor and are also largely made up of moderately to highly vesicular lapilli with scattered bombs. As in the SW wall deposit, a small fraction of bombs do contain some angular white lithic inclusions, but virtually all of the more typical fall lapilli are inclusion-free. Block-rich scoria fall deposits in the SSE wall rest sharply on fanglomerate basement on either side of a deep preexisting gulch now truncated by the Ubehebe wall. Scoria fall on what was the bottom of the gulch rests on basement at 770 m elevation; fallout on what was the gulch rim rests on basement at ~800 m elevation (Fig. 6). In both locations, scoria lapilli and bombs near the base of the deposit, some of which are dense with white lithic inclusions, range up to 40 cm, and scattered larger bombs are as big as 1 m. Two meters of the scoria fall make a ledgey outcrop on top of the basement,

but the deposit probably makes up as much as 30 meters of the slope above that is largely covered by scree from younger overlying Ubehebe deposits.

Bombs in the scoria fall are largest and most abundant mid-way along the south wall scoria exposure near the crater rim at 820 m elevation. Here, common 1-1.5-m-clasts are oxidized, flattened and agglutinated in a matrix of thoroughly oxidized scoria clasts seriate in size from a few centimeters to decimeters. The flattened bombs define a slope dipping $\sim 20^\circ$ northward toward the (younger) Ubehebe Crater (Fig. 7b). At this location they are overlain by a rim-ledge of black fallout from Little Hebe crater (discussed later). Nearby (westward), similar deposits that are tack-welded to slightly agglutinated are directly overlain by the tan and black stratified Ubehebe Crater deposits, which are oxidized (baked) pink in their lowest 15 to 100 cm (Fig. 7c). Clearly, the bombs in the initial “S” scoria fall were still hot when the Ubehebe Crater deposits were emplaced.

4.2 Overview of Amphitheater

The southern, middle and northern segments of the Amphitheater were each sources of phreatomagmatic deposits now exposed in nearby gulches (Fig. 9). Juvenile magmatic components have a range in vesicularities, including abundant nonvesicular, commonly breadcrusted black blocks containing angular white lithic inclusions. Near-source deposits from the southern and middle segments are also studded with angular sandstone blocks and fanglomerate cobbles reamed from the vents during eruptions. Similar lithics, although fewer and smaller, are included in deposits from the northern segment. Diminishing clast sizes and layer thicknesses away from source allow inference of the segment from which each of the packages of ejecta originated (Fig. 10). Overlying the ejecta derived from the three Amphitheater vents is a multi-part scoria fall derived from adjacent Crater P and a distinctive pink sandy interval widespread enough to be used as a marker horizon among the different gulches. The pink marker (~ 15 cm thick) is tentatively attributed to Crater W of the western crater group. The multi-layered Ubehebe Crater deposits conformably cap the sequence (Figs. 9, 10).

Because amphitheater deposits rest directly on basement along Gulches 1—4 and in the Big South Gulch, they were clearly erupted early in the overall sequence. Only in the upper reaches

of Gulch 1 is it clear that the “S” scoria fall preceded initiation of activity in the Amphitheater. At the head of Gulch 1, highly vesicular flattened scoria bombs up to 2 meters across and resting on fanglomerate are outsized relative to the eastward-diminishing sizes of dense bombs from the Amphitheater. The large vesicular bombs, accompanied by centimeters to decimeters of highly vesicular scoria-fall deposits, are nearly devoid of the white inclusions so ubiquitous in Amphitheater ejecta. Additionally, eastward-thinning Amphitheater fall layers in Gulch 1 are seemingly overthickened near the head of the gulch. We conclude that the outsized bombs and additional fall thickness are part of the “S” fall described above, that initiation of “S” scoria fall preceded all of the Amphitheater eruptions, but that there was either overlap in activity at the vents, or so little time between the “S” and Amphitheater falls that no sharp contact separates them. The opening Amphitheater explosions must have disrupted any initial “S” fall that had accumulated near the southern and middle Amphitheater vents themselves. Thus, deposit thickness, clast vesicularity, and bomb sizes at the head of Gulch 1 suggest that continuing simultaneous eruptions at the “S” vent and the southern and middle Amphitheater vents resulted in a fall deposit that locally includes contributions from all. Activity at these sites was over, however, by the time the eruption became focused in the northern segment, for deposits from that Amphitheater segment overlie all of the others (Fig. 10b).

The Amphitheater perimeter is delineated by arcuate ejecta rings that outline its southern, middle and northern segments, but lack of septa between the alluvium-filled segments suggests that none of them are deep, and/or it may reflect the lateral migration of successive explosions (after Valentine et al., 2015). The three were clearly distinct eruptive foci, however, and the gulches near each of the three segments expose deposits that have been divided into discrete units and traced to each of the segment sources. Most of the fall units thin quickly away from source but everywhere include larger ballistic ejecta in the same layer as fall lapilli. Only one unit has a large number of laterally emplaced layers, in which ballistic clasts and intercalated thin cross-bedded and plane-bedded layers result in a near-source deposit of hybrid (fall and flow) emplacement origin.

Stratigraphic observations establish the following sequence of eruptions from the main N-S crater cluster *after* scoria fall “S”:

- (1) an initial explosion breccia, which is largely comminuted basement material along with subordinate juvenile clasts that originated from the southern segment;
- (2) a multi-pulse fall sequence with a high fraction of juvenile material emplaced during a series of phreatomagmatic explosions from the southern and middle segments;
- (3) a strongly stratified phreatomagmatic phase with a low fraction of juvenile components that originated from the northern segment;
- (4) a largely magmatic lithic-poor fall that originated from Little Hebe Crater
- (5) a phreatomagmatic multi-layer lithic-rich fall that originated from Crater “P”.
- (6) multi-layered phreatomagmatic deposits, more voluminous than any other, with a high fraction of basement material excavated from Ubehebe Crater.

4.2.1 Southern segment: Opening blast

Amphitheater eruptions began in the southern segment. The opening blast deposit, up to 2 m thick in Big South Gulch (Fig. 9) includes as much as 40% comminuted basement, which makes up the orange-yellow sandy matrix. Angular sandstone chunks and cobbles as big as 1.3 m from the underlying fanglomerate make up another 40% of the deposit, with only ~ 20% being small, black, juvenile magmatic clasts. The deposit thins sharply to the north and east and is only patchily preserved owing (in part) to erosive scour by subsequent explosive episodes (Fig. 10a).

4.2.2. Southern and Middle segments: Three-part phreatomagmatic fall sequence:

Directly overlying the sandy opening blast deposit is a tripartite phreatomagmatic fall sequence well exposed near the mouths of Gulches 2, 3 and 4 and in Big South Gulch. There are no sharp contacts within the sequence, but upward transitions in clast sizes, sorting, and lithic abundances in the deposits are consistent from one gulch to the next (Fig. 10a). The deposit consists of two coarse fall units with bombs up to a meter long and between them a finer scoria lapilli fall that has few big bombs. As seen in Figure 9, the upper coarse fall has more abundant orange and white sandstone lithics than the lower coarse one, but lithics in both units are commonly up to 1 m and are as big as 2 m. Layer thicknesses and clast sizes in measured sections show that the lowest coarse unit is thickest near the middle segment of the Amphitheater, while the finer middle fall and coarse upper fall are thickest near the southern segment (Fig. 11). Many of the bombs in both coarse deposits were hot enough that they and their enveloping lapilli are tack-

welded to agglutinated, thus forming prominent ledges exposed on the gulch walls, especially close to source. Combined with the lack of sharp contacts between units, these relations lead to the conclusion that the deposits were emplaced during a continuous sequence that issued from both the southern and middle segments.

4.2.3 Northern segment: stratified phreatomagmatic unit

The northern segment of the Amphitheater is a shallow, 400-meter-long depression with a smooth, arcuate west-facing wall 25 meters high on its east margin, a truncated wall less than half that high on its west margin, and a northern margin that truncates the south side of the S-deposit remnant. Ejecta from this segment are largely milled basaltic clasts with a lesser (but present) pristine magmatic component, forming alternating tan sand-rich and coarser black lapilli layers in a deposit stratified on a centimetric to decimetric scale. Most of the deposit is made up of layers of poorly sorted black fall with angular basaltic clasts up to 6 cm in size (scattered to 10 cm), many of which are broken and dense, with and without white inclusions. A large fraction of these are thought to be clasts recycled from the preceding Amphitheater events. A few bombs are as large as 20-50 cm; these are likely juvenile. The tan layers make up ~20% of the deposit and, although they can be lensoid and discontinuous on a small scale, the layers are generally laterally persistent and are much like the black lapilli layers with a measure of coarse tan sand mixed in. The sand is derived from comminuted sandstone basement—only a few sandstone blocks survived intact. Small lithics in the deposit are largely rounded fanglomerate pebbles <6 cm in size.

Deposits ejected from the northern segment are best exposed in Gulch 1, where they are more than 10 m thick at the gulch mouth and thin to ~10 cm within ~400 meters farther upstream (Fig. 10b). Near the gulch mouth, the strata roll over from horizontal to dipping downward WNW into the Amphitheater, where they drape a pre-existing crater rim that was presumably excavated during the immediately preceding middle-segment phase (Figs. 10, 12). The deposits are probably thicker still along the NE wall of the northern segment, where windows through the draping Ubehebe Crater deposits expose several meters of outboard-(southeast)-dipping strata sharply overlain by northwest-dipping Ubehebe Crater deposits that plaster the inner wall. The

wall was explosively excavated during the described sequence, which deposited the outboard-dipping strata.

We interpret the northern segment deposits to have been emplaced by phreatomagmatic explosions that created pulsing showers of fallout, punctuated by ballistic ejecta of bombs and lateral blasts or surges. The explosions that reamed out the northern segment of the Amphitheater involved only a small component of juvenile ejecta, but ended with the purely magmatic eruption of Little Hebe, which deposited a distinctive black fall atop the stratified northern segment ejecta.

4.2.4 Northern segment: Little Hebe

Little Hebe, an agglutinated ejecta ring with a 20+-meter-deep circular crater 100 m wide, was constructed in the center of the northern Amphitheater (Fig. 13a). It was the source of a clean black scoria fall that directly overlies the juvenile-poor strata just described. Large bombs among the scoria lapilli provided enough heat to locally agglutinate or tack-weld the fallout, creating a meter-thick ledge that drapes the underlying juvenile-poor deposits at the mouth of Gulch 1 (Fig. 12). The fall deposit mantles part of the inner east wall of the northern segment, and makes a prominent ledge around the arcuate eastern end of the northern segment (Fig. 13b), as well as on top of the “S” scoria pile 150 m NNE (Fig. 7b).

Inside Little Hebe crater itself, a 4-to-5-meter-high ledge around its inner wall is made up of well-vesiculated, commonly oxidized, agglutinated scoria bombs and lapilli. A few of the largest bombs drape into the steep-walled crater, showing they were hot enough to deform into the crater after it formed. Because no layer of explosively distributed Little Hebe agglutinate fragments is present outside the crater rim (that might account for having reamed it), we surmise that either the spatter was emplaced as a column-surrounding ring, or that the crater formed by subsidence, a common occurrence in maar eruptions (Lorenz, 1986, 2007; White and Ross, 2011). There are no white inclusions in the Little Hebe scoria lapilli, and lithics are notably (nearly) absent in the deposits; sandstone lithics are very sparse in the crater walls, but the few are as big as 40 cm. This was almost exclusively a magmatic eruption. The highly vesicular scoria and scarcity of lithics contrast with the dense clasts so common in other Amphitheater deposits; this permits

tracking the Little Hebe fall through the Amphitheater gulches and into Big East gulch where it is still 6 cm thick ~600 meters southeast of the crater (Fig. 14a, b). The crater itself is mantled, inside and out, by thinly stratified Ubehebe Crater deposits, the lower few meters of which are pinkish orange (Fig. 13b). The oxidation is not stratigraphically controlled, for the color cross-cuts strata, showing it to be a post-emplacement feature. It underscores that Little Hebe spatter was still hot enough to oxidize deposits of the sequence-ending eruption of Ubehebe Crater.

4.3 Crater P

Also oxidized by being banked against hot Little Hebe agglutinate is a largely magmatic, multi-layer clast-supported and fairly well-sorted fall deposit that extends across gulches both east and west of the Amphitheater from its source at Crater P (Fig. 11d). Crater P fallout (“P” for “penultimate”) directly underlies the stratified Ubehebe Crater deposits and is thus the last fall before the eruption of Ubehebe Crater. Where wind has removed the tan sandy Ubehebe layers, Crater P lapilli fall remains as a distinctive black surface armour. This is seen clearly on the west rims of the middle and northern Amphitheater segments, where the black fall drapes into Crater P, and on some of the interfluves between Gulches 1—4 (Fig. 5). Black scoria fall in the same stratigraphic position exposed in the walls of Craters U and W is correlated with Crater P (Fig. 15). A four-part fall sequence (base not exposed) in the walls of Crater P includes two 1.5-2-meter-thick phreatomagmatic lapilli falls with conspicuous large sandstone lithics (a few to 90 cm), each overlain by thinner scoria falls (60 cm, 43 cm thick) that contain no large lithics, but do have some small broken fanglomerate pebbles. Scoria lapilli in the lower pair are somewhat coarser (1-5 cm, scattered to 10 cm, rare bombs to 60 cm) than in the upper two falls (1-3 cm), but all the subunits have a range of vesicularities, from moderately vesicular to dense. Only some of the smallest lapilli are highly vesicular. There are no sharp contacts between the falls, but thin (3-10-cm) fines-rich tan intervals form vague partings between layers. Similar strata are exposed in the inner wall of the adjacent alcove (see Fig. 3), where a window through the mantle of Ubehebe Crater strata exposes as much as 5 m of Crater P ejecta.

Despite the lack of well-defined internal contacts between subunits, this four-part package persists widely. Correlative fall resting on the agglutinated west flank of Little Hebe, as well as on the agglutinated mantle of Little Hebe fall near the mouth of Gulch 1, retain this four-part

character, although lithic sizes decrease away from vent. Wherever the Crater P fall rests on Little Hebe agglutinate, its base is oxidized. Across all Amphitheater Gulches (1—4), this black lapilli fall package is about 100 -150 cm thick, has scoria lapilli dominantly 1-3 cm, and stands out prominently in sharp contrast to the fine tan Ubehebe Crater layer directly overlying it (Figs. 5, 10). Southeast of the Amphitheater as far as 500 meters from source, the fall still retains its lithic-rich base and 4-part nature, even though partings between the subunits are defined only by minor additions of tan sand to the otherwise nearly continuous lapilli fall.

The multi-pulse nature of the ejecta is discernable southwest and west of the crater, as well (Fig. 15). The fallout is more than 465 cm thick in a deep gulch 100 meters SW of the Crater P rim (Sec 16). The gulch floor and the lowest 80 cm of the exposed deposit are rich in dense, locally agglutinated bombs, many 20-60 cm. This coarse material has no equivalent exposed in Crater P itself or in the P fall in Gulches 1—4. The overlying 4 meters, however, is a four-part black lapilli fall similar to that in the Amphitheater gulches, showing a range of vesicularity in the scoria lapilli, a basal layer with large blocks and abundant large lithics, and thin, diffuse, 5-cm grey partings between fall layers. The final fall in the package includes two large-lithic and block-rich intervals not present in the Amphitheater gulches, and was preceded by a 35-cm fines-rich interval that is thicker and more prominent than any seen within the same fall package in the Amphitheater gulches.

Such variations from one azimuth to another are not unexpected, and likely reflect non-radial, vent-reaming eruption pulses and asymmetric distribution of resulting deposits, including large ballistic clasts. The same lapilli fall exposed 600 m to the northwest in the south wall of Crater W (Sec. 18)—far from near-vent effects—is a single, 30-cm-thick black scoria fall with scattered small broken fanglomerate pebbles (typically <0.5 cm, and a few as large as 2 cm). It thins quickly northward to 15 cm on the north wall of Crater W, but clearly thickens toward Crater P. Lack of Crater P fall near the SW rim of Ubehebe Crater (Fig. 11) is likely due to scour from the immediately succeeding Ubehebe Crater eruptions.

4.4 Western Craters

We have identified ejecta from only three of the 7 shallow depressions that make up Western Crater group T through Z (Fig. 3). Only Craters W, Z and T have exposed ejecta clearly derived from them. The S-scoria fall is exposed at the base of each arcuate wall in Craters U, V, W, X and Z; Crater P fall is seen just below Ubehebe Crater strata in the walls of Craters U, V, W and Z; and Ubehebe Crater strata drape everything (Fig. 15). The Ubehebe strata mantle all the crater rims and fill Craters X and Y so completely such that their morphologic expressions are shallow enough as to leave open the possibility that they were never eruptive craters at all. Also unclear is whether or not Craters U and V ejected any material. The south wall of Crater U is arcuate like a crater, but it lacks a northern wall. Similarly, Crater V has a well-developed curved southern wall, but a much lower expression on its northern margin. It does seem likely, however, that the arcuate depressions U, V, X, and Y were at least foci of minor explosions, if not larger phreatomagmatic ones, and that any ejecta derived from them are now hidden beneath younger Ubehebe deposits.

The south wall of Crater W (Sec. 18, Fig. 15) exposes just over 7 m of a multi-layer lithic-rich sequence that overlies 24 cm of S-fall (base not exposed) and is mantled by ~2 m of Ubehebe Crater strata. On the north wall, where >4 m of the S-fall is exposed (no base), its lithic-poor nature is in sharp contrast to the overlying deposits that include meter-size orange and white sandstone lithics on both walls of Crater W. The large lithics require a local source. We divide these deposits into two packages:

- (1) a lower, three-part sequence with a poorly sorted, lithic-rich bottom and top, each with abundant large lithics in a non-stratified sandy matrix. The basal unit has a distinctive pink-orange matrix; the top unit is grey. A thinner stratified interval with wavy beds of alternating grey fines-rich and black lapilli-rich layers separates the two. The composite package is as much as 280 cm thick at the west end of Crater W (north wall), thins to less than half that only 100 meters away at the east end, and thins to 10 cm another 220 meters eastward in Crater U (Fig. 15). Both lithic sizes and eastward-thinning along the Crater W wall lead to the conclusion that this package erupted from nearby Crater Z (see Fig. 3), and not from Crater W. However, the mantle of Ubehebe Crater strata obscures Crater Z walls and the deposit is not exposed there.

(2) The second package is a three-part scoria-fall sequence (labeled “a, b, c” in Fig. 15, Sec. 18) with (a) a stratified lower 100-cm-unit that has three black scoria falls alternating with grey fines-richer intervals, including an upper fines interval ~20 cm thick; (b) a middle largely unstratified black lapilli fall ~80 cm thick; and (c) an upper 2-meter-thick grey lapilli fall with abundant large (meter-scale) white sandstone lithics. A fundamental contact within these packages is between the two black scoria falls (“a” and “b”) of the second package. The grey, fines-rich interval at the top of the lower stratified fall, and all the units above it, drape all of the underlying deposits. Thus, there was no Crater W when the basal S-fall and Crater Z deposits were emplaced. Eruption of the 100-cm-stratified fall initiated Crater W and subsequent fallout from continuing eruption at Crater W, followed by fallout principally from Ubehebe Crater draped its crater rim.

4.5 The Alcove

A distinctively semi-circular alcove ~150 m across that shares its southwest rim with Crater P and opens to its northeast into Ubehebe Crater is of uncertain origin. Its inner walls are draped by younger Ubehebe Crater strata, with only a few gullies incised enough on its inner western wall to expose the immediately underlying Crater P deposits. On the southeast shoulder of the alcove, agglutinated S-fall directly underlies the Ubehebe Crater mantle. No near-vent ejecta that might have erupted from the alcove is exposed nearby, except perhaps for a sharply thinning several-meter-thick grey scoria-lapilli layer atop the wedge of black S-fall scoria exposed on the southwest wall of Ubehebe Crater. A similar interval of grey lapilli is 40 cm thick on top of black S-fall in Crater U, and 10 cm thick in the same stratigraphic position in Crater W. Lapilli in this layer are small, dense, somewhat rounded, and dull grey, in contrast to the black, angular and markedly vesicular lapilli of the immediately underlying S-fall. Abundant sand and granules make a grey, gritty matrix. Contributions to this layer are likely from explosions that reamed out and “milled” previously emplaced ejecta. Although this layer could be the last pulse of the initial S-eruptive phase, it is also possible it was derived from small juvenile-poor eruptions centered in the alcove. The alcove may be sited above a tributary gulch to the main drainage that then ran through the later site of Ubehebe Crater. The walls of a small shallow horseshoe crater may later have been built up by mantling deposits from Crater P and Ubehebe.

4.6 Ubehebe Crater

Ubehebe Crater, as much as 800 meters across and 200 meters deep, is the largest and youngest of the craters (Fig. 2). The multi-layered black-and-tan phreatomagmatic deposits previously described by Crowe and Fisher (1973) mantle all ejecta from the rest of the crater group described above (Figs. 10, 15). Its deposits are as much as 50 m thick around most of its steep inner walls. Along its southern walls, however, Ubehebe deposits locally thin to less than half that, draping pre-existing topography that sloped significantly upward to the south. The underlying bedrock contact lies at an elevation of 725 m on the north wall and 770 m on the south. A pre-eruption network of gullies flowed northward and drained slopes both east and west of the present crater cluster. Ubehebe Crater deposits accumulated more thickly in old drainage axes than on interfluvies, and were later reincised mostly along their original routes. The deposits filled a large pre-eruptive drainage channel that once flowed from the southeast corner of the present crater toward the northwest, later truncated by the eruptions but still expressed as wide notches in the crater rim. A white sandstone outcrop (Figs. 6, 16) that rises conspicuously as much as 70 m above the present crater floor below the northwest notch also reflects pre-eruption topography. These suggest that there was appreciable relief on the fanglomerate surface before Ubehebe erupted, and that explosive reaming did not necessarily excavate the entirety of the present crater.

The dominance of tan, sandy intervals rich in basement lithics that make up the Ubehebe Crater deposits, and the milled appearance of the basaltic lapilli in the black intervals suggest that a large fraction of the explosions were repeated cycles of excavation and ejection of basement material and previously deposited S-fallout. A few of the black lapilli layers, however, have little sandy matrix and may consist mostly of juvenile fallout. Strikingly consistent thicknesses of many of the individual deposit layers, and mantling of underlying topography without thickening or thinning in gullies, suggests that most of the Ubehebe layers were deposited as fall (Figs. 4, 12).

Thick tan fine intervals that dominate the upper third to more than half of the Ubehebe strata in locations well away from the crater rim are markedly different. These clearly thicken in paleogullies (Fig. 4) and are laterally emplaced. Thus, we think that most of the black, brown,

and tan Ubehebe layers were deposited by explosive pulses that showered the area with basaltic lapilli, fanglomerate lithics, and ballistic bombs, while finer material was transported laterally at the same time. It is difficult to assess what fraction of the black lapilli in the Ubehebe Crater deposits are recycled S-fall clasts and which are new juvenile additions, although the dominantly milled appearance of a large proportion of the clasts suggests the former.

The clearest example of a juvenile magmatic component is exposed on the crater floor. After the powerfully explosive evacuation of the Ubehebe Crater, a small magmatic pulse ejected black scoria bombs and lapilli that agglutinated against the white sandstone wall at the bottom of the crater (Figs. 6, 16). There is a small compositional difference between this latest-stage ejecta and basaltic ejecta from the other craters and even from earlier Ubehebe Crater ejecta (Fig. 17). Only one sample, from near the top of the Ubehebe Crater deposits west of the crater, is still more mafic (48.7 %SiO₂) than the crater-floor spatter. Nonetheless, the narrow compositional range (Fig. 17) of our 30 samples suggests ascent of a single magma batch.

5. Discussion

5.1 Duration of eruptive sequence

The established eruptive stratigraphy, field observations, chemistry, and paleomagnetic directions combine to show that all eruptions from the Ubehebe cluster happened over a short time interval because:

- (1) All the units are conformable. There is no alluvial channeling or even any shallow rilling between layers.
- (2) Whole-rock composition of samples spanning the stratigraphic sequence shows little variation (Fig. 17, Appendix 1). Although not all identical, and with some suggestion of possible fractionation, they are, overall, quite similar to one another and look like a monogenetic group.
- (3) Five locations and four different units were drilled for paleomagnetic directions (Figs. 3, 15). The drilled units span the entire eruptive sequence, from the basal coarse falls at both north and south ends of the eruptive alignment, to Little Hebe in the middle spatially and temporally, to the youngest agglutinated spatter on the floor of Ubehebe Crater. The tight cluster of Ubehebe data requires a time frame short enough that the magnetic pole remained stable over the course of the

eruptions, inferentially no longer than a decade for the entire eruptive sequence (Fierstein et al., 2016, Champion et al, in prep).

(4) Wherever the last-emplaced Ubehebe Crater deposits overlie tack-welded to agglutinated spatter and bombs from the earliest erupted units in both the north and the south, the Ubehebe deposits are oxidized. Thus, the earliest ejecta remained hot enough to oxidize the youngest emplacement package. The thermally oxidized deposits, only a few meters thick, require that the time frame for the entire eruptive sequence was very short, probably less than a year.

5.2 Eruptive inferences

The long-standing model of progressively deepening phreatomagmatic explosions with drawdown of the water table (Lorenz, 1986), as modified by Valentine and White (2012) to include explosions at any level in the conduit, has been used to explain the formation of maar and tuff-ring deposits. Gutmann (2002) suggested that relative rates of magma and water supply control eruption style; Carrasco-Núñez et al. (2007) suggested that fluctuating water—magma interactions may reflect a migrating locus of explosions; Ort and Carrasco-Núñez (2009) suggested that lateral vent migration is related to overall dike length. All of these ideas bear consideration at the Ubehebe cluster, since the main craters in the cluster are aligned north-south, and the deposits described above show various degrees of magma-water interaction. The Ubehebe cluster, perched on a sloping indurated Miocene fan surface ~120 m above the adjacent valley floor, raises questions about the mechanisms of such explosive interactions in the arid Death Valley environment, where average rainfall over the last century has been ~ 56 mm/year (Western Regional Climate Center, <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca2319>). Sasnett et al. (2012) explored the possibility (and concluded negatively) that maar eruptions at the Ubehebe cluster a few millennia ago might have indicated a wetter climate. Although study of grainsize, dispersal, and eruption dynamics associated with crater formation and emplacement processes of the deposits is beyond the scope of our stratigraphic study, we do list below several observations that bear upon such questions:

- (1) Most of the craters in the Ubehebe cluster are shallow, with rim height:width ratios between 1:20 and 1:10. Only Ubehebe Crater is deep, with an aspect ratio of ~1:5. This difference in morphology may represent short-duration eruption foci in the

- shallow craters and a relatively longer one in the deeper Ubehebe Crater, where explosions persisted long enough to mine deeper into bedrock (after Lorenz, 1986).
- (2) The northern segment of the Amphitheater was likely widened to 400 meters by repeated shallow explosions. Once the eruption became magmatic, it was focused centrally to produce the Little Hebe spatter ring and fall.
- (3) Water now collects in the crater bottoms only rarely as shallow ephemeral ponds. Most of the time, the accumulated tan silt on the crater floors breaks into polygonal mud cracks. We have seen no evidence for a lake or significant standing water in any of the crater bottoms.
- (4) The indurated fanglomerate bedrock has an apparent low porosity; fractures are the most probable avenue for water-magma interaction. We note, however, that Ubehebe Crater, the largest, deepest, and perhaps longest-lived of the cluster, erupted along the path of a large paleogully.
- (5) The north-south vent alignment of the main Ubehebe cluster, with compositionally similar ejecta, seems most likely due to emplacement of a single dike that followed the regional structural trend of the Basin and Range. The line of western craters U—Z, perpendicular to this trend, seems to require a separate (but related) diverging dike or sill, as suggested by Muirhead et al. (2016) for the Hopi Buttes volcanic field. Perhaps crater T requires a third?
- (6) Ejecta from the craters include juvenile clasts with a range of vesicularities and lithic material entirely derived from bedrock units exposed in today's shallow gullies. The proportion of juvenile-to-lithic material is variable, as is the proportion of vesicular versus dense juvenile clasts; both characteristics are used in defining stratigraphic units. This variability suggests that the water-magma ratio varied throughout the eruption.

5.3 Reconsideration of the ^{10}Be exposure ages

Sasnett et al. (2012) measured $^{10}\text{Be}/^9\text{Be}$ for 15 alluvial cobbles (10–20 cm) of quartz-rich accidental ejecta (sandstone, quartzite, granite) embedded in the topmost layer of the 50-m-thick pile of basaltic ejecta along the east rim of Ubehebe Crater. The Paleozoic quartzite and Mesozoic granite cobbles were part of a thick Miocene fan deposit of sandstone and

conglomerate, which had been sharply dissected before the Ubehebe eruption by at least five steep-walled ephemeral arroyos that run only during occasional cloudbursts. One large pre-eruptive arroyo crossed the subsequent site of Ubehebe Crater from southeast to northwest. The Ubehebe ejecta rest directly upon the Miocene fan deposit, and the explosive eruption could have excavated the cobbles from active arroyo floors, walls, or interfluvies (with varied exposure durations) as well as from unexposed depths in the fan. The 15 cobbles studied were ejected at the very end of the crater-forming sequence of phreatomagmatic explosions, from Ubehebe Crater alone.

The 15 samples came from three clusters of five, all 15 within 600 m of each other on the present-day surface. Cobbles from the northeast cluster gave ages of 0.8, 1.5, 1.5, 1.7, and 1.8 ka; those in the east cluster gave 0.95, 1.1, 1.9, 2.0, and 2.1 ka; and those in the southeast cluster gave 1.3, 2.0, 2.9, 3.3, and 5.1 ka (Sasnett et al.; Fig. 2). Stratigraphic correlations show that all 15 were ejected from Ubehebe Crater itself and were not recycled from any of the preceding craters, the lapilli-grade ejecta of which had never extended to the area subsequently excavated at Ubehebe Crater. The only pre-Ubehebe ejecta within the area excavated were juvenile scoria fall (unit S), which is nearly devoid of accidental lithics. Thus, the hypothesis of Sasnett et al. (2012) that some of the ejecta were recycled from earlier craters is untenable.

The crater-rim surface from which the cobbles were collected may or may not be strictly primary. The windy rim has been subject to deflation of fines, leaving a lapilli-dominant armor that includes a scattering of coarser clasts—basaltic and accidental. Continuity of the thin-to-medium bedding of the basaltic fall deposit, however, suggests that any deflation (and thus differential exposure of the three sample clusters) has been less than one meter. Nonetheless, deflation uncertainty means that small differences in effective post-eruptive exposure duration cannot be excluded.

As the 15 cobbles were all deposited by the same ejection pulse at Ubehebe Crater, which was apparently the last of 100 or more staccato outbursts at that crater, then how is the range of exposure ages to be explained? The following possibilities are suggested. (1) Most of the cosmogenic ^{10}Be was inherited from exposure intervals of varied duration on fan surfaces, gully walls, and active arroyo floors prior to the eruption. If the youngest ages (0.8–1.1 ka) represent true exposure duration of (formerly long-buried) cobbles with no inheritance, then they might provide an age for the eruption.

(2) If wind has slightly deflated the low-relief surface, then successively exposed cobbles could have added varied amounts of post-eruptive ^{10}Be to any pre-eruptive ^{10}Be inheritances, thus further complicating the range of apparent ages. As an unlikely extreme, if none had any inheritance, then the 5.1-ka cobble might date the eruption, and all the rest might have been progressively uncovered.

(3) The average of the 15 ages is about 2000 years, which is similar to the ca. 2100 years estimated by paleomagnetic determinations by D. Champion for products of the Ubehebe Cluster (Calzia et al., 2016). If the eruption took place about 2100 years ago, then three of the 15 ages reflect inheritance, eight reflect incomplete post-eruptive exposure owing to temporary burial and later deflation, and four are about right (1.9–2.1 ka).

We favor alternative (3), which embraces elements of (1) and (2). In any case, without the detailed stratigraphic analysis established in the present paper, recycling of cobbles from earlier craters could not have been dismissed, ejection of the 15 cobbles by Ubehebe Crater alone could not have been proven, and the brief monogenetic episode of the whole crater cluster could not have been demonstrated.

6. Conclusions

Despite lithologic similarities, individual fall units can be traced outward from source by recording layer thicknesses, maximum scoria and lithic sizes, and juvenile clast textural variations. Eruptions at the Ubehebe cluster began with its largest magmatic event—initial scoria “S”. A sequence of phreatomagmatic events followed in the Amphitheater, destroying the southern part of the initial pile of scoria “S”, and ended with the magmatic Little Hebe spatter vent. Continued phreatomagmatic events at the Western Craters were followed by largely magmatic eruptions at penultimate Crater P. The final stage involved explosions that effectively excavated the substrate while ejecting little juvenile material at the largest and northernmost of the craters, Ubehebe Crater. These events destroyed the northern part of initial scoria pile “S” and blanketed the entire landscape with layers of recycled scoria, basement lithics, sand derived from comminuted basement, and some amount of juvenile ash. Its largely juvenile-poor deposits drape all of the others, thicken into paleogullies, and thin over the other newly created crater

rims. The reconstructed eruptive sequence and the varied proportions of juvenile, recycled, and lithic constituents record changing eruptive styles (juvenile-poorer and richer phreatomagmatic and magmatic) throughout.

Eruptions from the Ubehebe Crater cluster were short-lived, emplacing a sequence of deposits from 14 craters, apparently in late Holocene time, 10 of which are known to have produced recognizable deposits. Evidence that all Ubehebe strata erupted within a short time includes: (1) Deposits from the many Ubehebe vents make a multi-package conformable sequence that drapes paleo-basement topography and exhibits no erosive gully between emplacement units. (2) Crater rims that formed early in the eruptive sequence are draped smoothly by subsequent deposits, there having been no interim notching of the crater walls. (3) Tack-welded to agglutinated spatter and bombs that erupted early and midway in the sequence remained hot enough to oxidize overlying emplacement packages. (4) Paleomagnetic mean site directions corroborate the short eruptive duration (Fierstein et al., 2016, Champion et al., in prep), for there is no evidence of geomagnetic secular variation among early, middle and late-erupted units of the cluster. (5) The narrow compositional range in major and trace elements of juvenile components from every eruptive package suggests a common magmatic batch that erupted within a short time. Evidence in-hand thus virtually requires that the Ubehebe cluster of craters erupted over a brief time interval, likely days to weeks—conceivably months, but certainly not protracted over centuries.

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Figures

Fig. 1. Aerial view of the Ubehebe Crater cluster with ejecta draping a well-developed drainage network incised in Miocene fanglomerate (Google Earth image). Gullies that run west and north empty downstream into (typically dry) Lake Rogers (out of view). Fourteen labeled craters

include the large Ubehebe Crater; a triad that make up the northern, middle, and southern segments of the Amphitheater; Little Hebe crater nested within the northern Amphitheater segment; a remnant of the first scoria vent (S) truncated by subsequent eruptions; and Craters P and T – Z. The semi-circular alcove between Crater P and Ubehebe Crater may have been initiated by small explosions, but most of its shape is constructional from mantling deposits derived from Crater P and Ubehebe Crater. An access road from the east curves around the north side of Ubehebe Crater and ends in a parking lot on the west rim. Black square on the inset map shows location of Ubehebe Crater cluster in Death Valley, California (CA).

Fig. 2. View east toward the west-facing wall of Ubehebe Crater. Most of the 165-m-high wall is made up of orange and yellow Miocene fanglomerates and sandstone layers, overlain by ~50 meters of thinly stratified tan and black phreatomagmatic ejecta from Ubehebe Crater.

Fig. 3. Outlines of the rims of the 14 depressions that make up the Ubehebe Crater cluster, with names as in Figure 1. Little Hebe (LH). Two main gulches that expose much of the stratigraphy are Big East gulch that drains north then east, and Big South gulch that drains west then north. Gulches that drain into the Amphitheater are numbered (1—4); measured sections (blue circles); sample locations (yellow circles); paleomagnetic drill sites (red triangles; see Champion et al, in prep).

Fig. 4. View southward from the head of gulch 1, with initial black scoria fall (S-fall) mantling pre-existing gullies in the Miocene fanglomerate. Tan and black phreatomagmatic layers from Ubehebe Crater drape the preexisting topography, thickening in gully axes and thinning over ridges.

Fig. 5. View NNE from rim of Gulch 4 toward Gulch 1 (Gulch 2 is hidden by walls of Gulch 3). Gulches drain northwestward (left) toward the Amphitheater basin; sharp ridges between gulches are marked with yellow dashed lines. All units are conformable: Lithic-rich Amphitheater (A) deposits, the overlying black lithic-poor Crater P (P) fallout, and capping tan Ubehebe Crater (UC) strata are all exposed in each of the gulches with no channeling or rills between units.

Crater P fallout is ~1 to 1.5 meters thick across the 400-m-stretch from Gulch 4 to Gulch 1, but Amphitheater deposits thin quickly up-gulch (see Figure 10b). Gulch 3 is ~11 m deep.

Fig. 6. View SSW toward west and south walls of Ubehebe Crater that expose the truncated deposits of initial scoria eruption “S”. On the west wall, a prominent black wedge of scoria fall as much as 15 m thick rests on pale orange sandstone basement at 770 m elevation and is overlain by ~20 meters of thinly stratified tan and black layers from Ubehebe Crater. The SW crater rim is as much as 195 m above the crater floor. The scoria pile in the SW corner is largely unconsolidated and scree-covered, but several remnants of tack-welded ledges up to a meter thick are preserved near the top of the pile. An agglutinated and strongly oxidized pile of large bombs makes a prominent diagonal ledge on the south wall, with many of the largest flattened bombs (as big as 1-2 meters across) being strongly flattened and dipping ~20° into Ubehebe Crater. In the SE corner, a prominent gully follows the same course as a major pre-existing gulch that once drained NW across the site of the present Crater. On either side of the gully are several meters of intact S-fall that mantled the old topography and now make black, block-rich ledges resting directly on the orange basement fanglomerate at 770-m and 800-m-elevation. A low notch in the NW corner of Ubehebe Crater also reflects the pre-eruptive drainage, which was destroyed when Ubehebe Crater erupted; the white sandstone basement ridge (lower right) formed its right (East) bank. The final ejecta from Ubehebe Crater is an agglutinated scoria fall plastered against the base of the white sandstone ridge (see Figure 16).

Fig. 7a. Agglutinated and flattened bombs from initial S-scoria fall are up to 2 meters across and rest directly on orange cobble fanglomerate in Big East Gulch, 750 SE of the agglutinated scoria pile on the S rim of Ubehebe Crater (shown in Fig. 7b). Overlying Ubehebe strata are 8 m thick.

Fig. 7b. Flattened, agglutinated and strongly oxidized bombs from the initial S-fall define a slope dipping ~20° northward into Ubehebe Crater. They are overlain by a 75-cm black ledge of locally tack-welded to agglutinated scoria from Little Hebe.

Fig. 7c: The basal meter of stratified Ubehebe Crater deposits on the crater’s south rim were oxidized when emplaced onto still-hot agglutinated scoria from the initial S-fall. The heat-

oxidized deposits require that there was little time between their emplacements. Bush on the skyline is 1 m high.

Fig. 8: Distribution of initial scoria fall “S” with measured thickness in centimeters. Intact fallout as much as 20 cm thick 1.5 km NNW, and 6 cm thick 4 km ENE of vent show that this was the most widespread and largest of any of the Ubehebe cluster eruptions.

Fig. 9. Measured section in Big South Gulch is 11.7 m thick and rests on fanglomerate basement (shadowed gulch bottom). The opening blast deposit (2 m thick) from the south Amphitheater segment is orange because it includes as much as 40% comminuted basement, which makes up the sandy matrix. The black overlying 3-part fall originated from the southern and middle Amphitheater segments and includes abundant orange and yellow sandstone lithics in the lower and upper packages. The black fall from Crater P (P) is as much as 135 cm thick just out of view (left), where it is capped by 10-15 cm of tan sand—all that remains here of the largely eroded Ubehebe Crater (UC) deposits. The 15-cm-thick pink sand layer is seen widely throughout the Amphitheater gulches. Local low-angle cross bedding suggests wind reworking during a brief hiatus between the Amphitheater eruptions and Crater P.

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Fig. 10a. Stratigraphic columns across mouths of Amphitheater gulches 1, 2, 3, 4 and Big South gulch show that northern-segment-derived ejecta thin southward, southern-segment-derived ejecta thin northward, and Crater P ejecta maintain a similar thickness across the 400-meter stretch. Ubehebe Crater deposits thicken in gully axes, and have been severely wind-eroded from many gulch interfluves. Location map shows numbered sections.

Fig. 10b. Stratigraphic columns up Gulch 1 show all of the Amphitheater fall deposits thin quickly away from their source vents. Clast sizes decrease up-gulch within each fall layer. In contrast, scoria bombs 1-2-meters long resting on basement at the head of the gulch is evidence that those are derived from the initial S-fall eruption near the south rim of Ubehebe Crater, and not from the Amphitheater.

Fig. 11: Fallout distribution maps for Amphitheater units and Crater P with location of thickest deposits for each layer used to identify vent location. (a) The Amphitheater opening blast is thickest near the southern segment; (b) The multi-part phreatomagmatic deposits that were emplaced during a continuous sequence issued from both the southern and middle segments; (c) Largely juvenile-poor deposits are very thick around their source in the northern segment; (d) Thick Crater P fallout, although only shallowly incised in and near the crater, clearly erupted from this vent. Deeper incision in the SW corner of the adjacent alcove shows their shared wall is largely constructional, built of proximal Crater P ejecta that does not have a correlative fall layer preserved on either alcove rim that opens toward Ubehebe Crater. Lack of any Crater P fall there is likely due to scour by Ubehebe Crater eruptions that immediately followed penultimate P-fall.

Fig. 12: Little Hebe agglutinated scoria ledge drapes over the black-tan, stratified, largely juvenile-poor ejecta from the Northern Amphitheater segment. Strata in the lower unit are sub-horizontal in most of Gulch 1, but roll over from horizontal to dipping downward WNW (left) into the Amphitheater, where they drape a pre-existing crater rim presumably excavated during eruption of the middle Amphitheater segment. The deposit is stratified on a centimetric to decimetric scale with a large fraction of milled (recycled) clasts. Black and tan Ubehebe Crater strata overlie black fall deposits from Crater P.

Fig. 13a: View NW into the nearly circular, 100-meter-wide and 20-meter-deep Little Hebe crater located in the center of the northern segment of the Amphitheater. The 4-5-meter-high reddish-brown ledge around its inner wall is made up of oxidized, agglutinated scoria bombs and lapilli with almost no basement lithics. Thinly stratified Ubehebe Crater deposits mantle the Little Hebe rim and inner crater walls, which are lower on the SE side.

Fig. 13b: View eastward, looking over the low east rim of Little Hebe crater (note 1.8-meter-tall hiker on rim) toward the NW-facing inner wall of the northern Amphitheater segment. The lower few meters of thinly stratified Ubehebe Crater deposits (UB strata) are pinkish orange and rest directly on the agglutinated ledge of Little Hebe scoria bombs. The oxidation that cross-cuts strata is a post-emplacement feature and shows that Little Hebe spatter was still hot when the

Ubehebe Crater deposits were emplaced. Agglutinated fall exposed in Little Hebe crater walls is equivalent to the meter-thick agglutinate ledge that wraps around the inner wall of the northern Amphitheater, which is the same draping ledge as in Fig. 12. The scoria ledge rolls over and covers the underlying juvenile-poor ejecta that was emplaced during excavation of the northern Amphitheater, and is preserved as a black armour along the south end of the arcuate wall.

Fig. 14a. Distribution map of Little Hebe fall; thickness in centimeters.

Fig. 14b. The well-vesiculated scoria and scarcity of lithics in Little Hebe fall are in marked contrast to the dense clasts and common lithics in Amphitheater ejecta. These distinctive characteristics helped track the fall through Amphitheater gulches.

Fig. 15. Stratigraphic columns in the Western Craters and correlation with Amphitheater stratigraphy. Colors and labels are the same as in Figure 10. Location map shows numbered sections. Few sections are exposed to basement, as indicated by ‘base not exposed’ (bne). Initial scoria fall “S” is not seen widely in Amphitheater gulches, but large well-vesiculated scoria bombs resting on fanglomerate at the head of Gulch 1 are evidence that S-fall is present there. The grey scoria fall directly on top of black S-fall in Craters U and W may be related to it, or alternatively derived from the alcove (red “a” in inset). Crater P (P) is the penultimate eruption prior to that of Ubehebe Crater and is found widely in the Amphitheater gulches to the southeast as well as in the Western Craters. Little Hebe (LH) is present widely in Amphitheater gulches, but is only 5 cm thick to the northwest in Crater U. Explosive bursts from Crater T (T) produced lithic-rich ejecta that thins eastward and is intercalated with that of Crater P. Crater W ejecta are thick in its crater walls and include meter-sized lithics; the deposits thin and fine eastward toward Crater U. A draping layer of grey sand (presumed from Crater W) mantles the crater rim excavated by initial eruption of Crater W. All subsequent layers drape the underlying deposits; Crater W was not yet formed when flat-lying Crater Z (Z) deposits were emplaced. Three subunits of Crater W deposits are labeled (a), (b), and (c). Red arrows indicate the *stratigraphic* position of the 5 sites drilled for paleomagnetic direction. See Figure 3 for *locations* of drilled sites.

Fig. 16. Photo of last Ubehebe Crater agglutinated scoria against white sandstone outcrop at the bottom of Ubehebe Crater (see location in Fig. 6). Paleomagnetic direction of this final ejecta out of Ubehebe Crater is the same as that of initial scoria fall “S” (Fierstein et al., 2016; Champion et al., in prep).

Fig. 17. Whole-rock chemistry for samples representing the entire stratigraphic sequence shows little variation, apparently a monogenetic group. (a) TiO_2 vs SiO_2 ; (b) Ba vs SiO_2 . Ubehebe Crater (UB).

Western Crater Group

Z
Y X W V U

Ubehebe Crater

alcove

S

Little Hebe

northern

middle

southern

T
Crater P

Amphitheater

117°27'30"

117°26'30"

fanglomerate basement

Ubehebe Crater strata

S-fall (30 cm)

UC

P

GULCH 1

A

Ubehebe Crater

(~5 m)

Ubehebe Crater

(~1 m)

Crater P

GULCH 3

UC

(~5 m)

Amphitheater

GULCH 4
(main gully)

Crater P
(1.5 m)

GULCH 4
(small spur)

pre-existing gulch

alcove

scoria wedge

Ubehebe Crater
strata

770 m

800 m

scoria fall
on basement

agglutinated
bombs

scoria pile

(770 m)

sandstone
basement

sandstone
basement

final Ubehebe
agglutinate

Crater P

pink sand

Upper coarse
lapilli-rich

Clean
lapilli fall

Lower coarse
lithic-rich

Opening
blast

Fanglomerate

2 m

Sec 11

Opening blast:
Southern segment, Amphitheater
(thickness in cm)

3-part lower sequence:
Southern +Middle segments,
Amphitheater
(thickness in cm)

Stratified unit w/lithics: Northern segment
(thickness in cm)

Crater P
(thickness in cm)

fallout interval
from Crater P

Ubehebe
Crater strata

Draping tack-welded ledge
from Little Hebe

> 10 m

draping strata from
northern segment

Tack-welded ledge

stratified, mostly phreatic deposits
from northern segment

Mouth of Gulch 1

Tack-welded agglutinate ledge
from Little Hebe

UB strata

Little Hebe East crater wall

Little Hebe: agglutinated well-inflated scoria fall

(thickness in cm)

Crater T

100 cm

Crater P

Crater W

Crater U

Amphitheater gulches

paleomag.

UBEHEBE CRATER

P

T

AMPHITHEATER

S

alcove?
initial "S" fall

fanglomerate
basement

final agglutinate